Patent
PDNO 10991744-4

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of:
Janice Nickel

Serial No. 09/981,277
Filed: October 17, 2001

: Confirmation No. 8131

: Examiner Ken Pierre
: Group Art Unit: 2822

For: METHOD OF FABRICATING AN MRAM DEVICE INCLUDING SPIN DEPENDENT TUNNELING JUNCTION MEMORY CELLS

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RULE 131 DECLARATION BY INVENTOR

I, the undersigned, declare that:

1. I am the sole inventor in the above-captioned patent application.

2. I prepared an invention disclosure entitled "Process for controlling magnetic coupling, and improving device uniformity in SDT junctions used for MRAM applications (the "Invention Disclosure"). A copy of the Invention Disclosure is attached. I signed and dated the Invention Disclosure on June 3, 1999 and submitted the Invention Disclosure to the intellectual property department of Hewlett-Packard Company.

3. All statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

13-Sept-2002
Date

Janice Nickel
Janice Nickel

HEWLETT PACKARD

INVENTION DISCLOSURE

PDNO 1099 744 | Attorney TRC
Date Received 6-4-99 ISR

Company Confidential: The information contained in this document is COMPANY CONFIDENTIAL and may not be disclosed to others without prior authorization.

Please submit this disclosure to the HP Legal Department as soon as possible. No patent protection is possible until a patent application is authorized, prepared and submitted to the Government.

Descriptive title of invention:
PROCESS FOR CONTROLLING MAGNETIC COUPLING, AND IMPROVING DEVICE UNIFORMITY IN SDT JUNCTIONS USED FOR MRAM APPLICATIONS

Name of project: MAGNETIC DEVICE TECHNOLOGY
Product name or number: MRAM

The invention is described in my lab book # 2828 or in the following other records: ______

Has the invention been built or tested? No ☐ Yes ☒ Date built or tested: May 1999

Was a description of the invention published or are you planning to publish? No ☒ Yes ☐
Date and location of any actual or proposed publication of the invention: ______

Was a product including the invention shown, announced or sold? No ☒ Yes ☐ Date and location of any actual or proposed announcement, offer to sell or sale of the product: ______

Name and date of anyone outside HP to whom invention will be or has been disclosed: ______

If any will occur within three months, please call your IP attorney or the Legal Department at 1-857-2542 or 415-857-2542.

Government Contract: Was this invention made under a government contract? No ☒ Yes ☐
Government agency and contract number: ______

Description of invention: Please preserve all records of the invention and attach additional pages giving the following:
Each additional page should be signed and dated by the inventor(s) and witness(es)

a. Problems solved by the invention.
b. Prior solutions and their disadvantages (If available attach copies of relevant technical articles or patents).
c. Description of the construction and operation of the invention (include appropriate schematic, block and timing diagrams; drawings; samples; graphs; flowcharts; computer listings; etc.).
d. Advantages of the invention over what has been done before.

Signature of Inventor(s): PLEASE SEE BACK OF FORM FOR ADDITIONAL REQUIRED INVENTOR INFORMATION.

I(we) this date June 3, 1999 submit this invention disclosure pursuant to my(our) employment agreement.

Emp. Number	Name	Signature	Telnet #	Mail Stop	Entity Name and Lab Name
461217	Janice Nickel	Janice Nickel	7-5299	2U-8	0419-5213 ISTL TPD
-0-					
-0-					

If more than three inventors, please sign on an additional disclosure form and attach to this page.
Please try to obtain the signature of the person(s) to whom the invention was first disclosed.

Signature of Witness(es):
The invention was first explained to and understood by me (us): 6/4/, 1999.

Print Name	Signature	Date of signature
MANOJ K. BHATTACHARYYA	[signature]	

Rev. [illegible]

Received from < 949 454 0898 > at 10/9/02 11:27:58 AM [Eastern Daylight Time]

Invention Disclosure
May 13, 1999

Process for controlling magnetic coupling and improving device uniformity in SDT junctions used for MRAM applications

Janice Nickel
Magnetic Device Technology Project, Thin Film Department,
Information Storage Technology Laboratory, Hewlett Packard Laboratories

Highlights of Invention:

--Allows control of magnetic interactions such that magnetic response loop can be "tuned" to be symmetric about zero field.

Prior art:	cross your fingers,
Invention:	control over ferromagnetic coupling, so it can exactly cancel antiferromagnetic coupling of the device.

--Increases device uniformity across the array

Prior art :	resistance varies 28% across the array
Invention:	resistance varies 8% across the array

--Allows reduction of device resistance

Prior art:	barrier thickness determined by the grain heights of the bottom electrode
Invention:	reduce grain height of bottom electrode, allowing thinning of barrier.

--Increases yield of devices

Prior Art:	Large number of shorts in the arrays at low resistance design center.
Invention:	Process results in fewer shorted devices in the MRAM arrays.

Janice Nickel 6/3/99

6/4/99

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Invention Disclosure
May 13, 1999

Process for controlling magnetic coupling and improving device uniformity in SDT junctions used for MRAM applications

Janice Nickel
Magnetic Device Technology Project, Thin Film Department, Hewlett Packard Laboratories

Magnetic Random Access Memory (MRAM) utilizing Spin Dependent Tunneling (SDT) junctions as memory elements is currently in the research phase at several prominent laboratories. SDT junctions consist of a multilayer stack of materials. Figure 1 shows a typical stack. It starts with a Ta seed layer, followed by NiFe to establish a (111) orientation of the crystal structure. This orientation is required for the subsequent antiferromagnetic (AF) pinning layer. The pinning layer provides a large exchange field, which holds the magnetization of the pinned ferromagnetic (FM) layer in one direction. There are optional interfacial layers sandwiching a dielectric tunnel barrier, followed by the sense ferromagnetic layer (whose magnetization is free to rotate in an applied field), and a protective Ta capping layer.

These are not the only materials nor configurations that can be used in a SDT junction. Other FM materials such as CoFe, may be used as the pinned and sense layer, any material may be used as the interfacial layer, although a high spin polarized material is desirable. Any dielectric and some semiconducting materials may be used as the tunnel barrier. Alternate configurations include using a hard magnet instead of an AF pinning layer; although it has been shown that the hard magnet becomes demagnetized with cycling of the sense FM layer. Another possibility is to place the AF pinning layer on the top, instead of the bottom of the stack; however, this configuration does not create the (111) orientation necessary for high exchange fields.

A SDT junction exhibits tunneling magnetoresistance (TMR) with the application of a magnetic field. Values of TMR as high as 40% at room temperature have been observed. The relative orientation, and the magnitude of the spin polarization, of the FM layers on either side of the dielectric layer determine the magnitude of the signal produced. When the magnetization of the two FM layers are parallel, the junction exhibits a low resistance (R) state; when they are antiparallel, the junction exhibits an high R state.

For the SDT junction to serve as a memory element, there must be two stable zero field states: i.e., one must be able to achieve a high R state after application and removal of a magnetic field in one direction, and achieve a low R state after application and removal of a magnetic field in the opposite direction. Optimally, the magnetic field required to switch the state of the element would be equal in magnitude for either direction. For this to occur, the hysterisis curve of the sense FM film needs to be centered around zero field. Equivalently, the electrical response to a magnetic field (at fields below the exchange field) should exhibit a loop centered about zero field. Figure 2 shows an optimal response curve of a SDT junction.

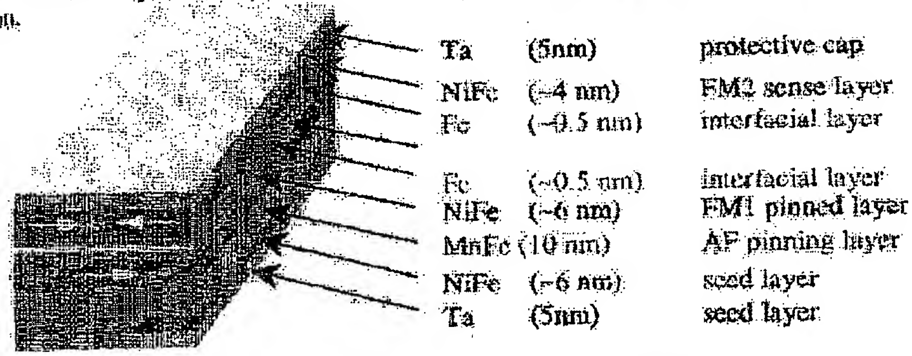

Figure 1: Typical materials stack for SDT junction.

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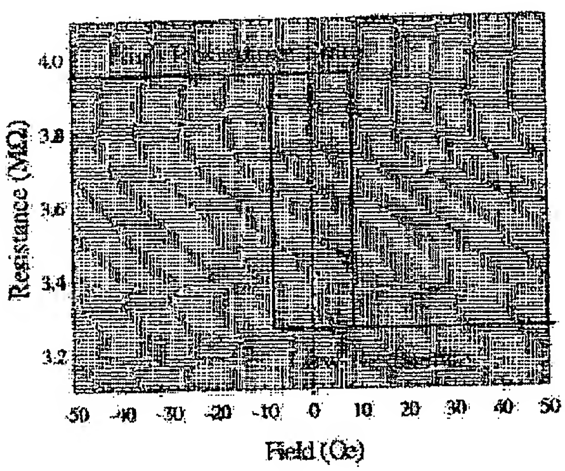
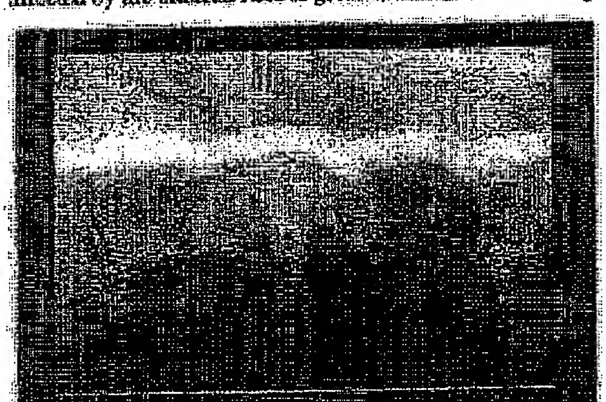


Figure 2: Optimal electrical response to applied magnetic field of a SDT junction. At zero field, there are two distinct states, corresponding to "0" and "1" memory element values. The field required to switch the memory state is small and equal in magnitude in both directions.

Magnetic interactions between the FM layers tend to displace the electrical response from zero field. Two primary interactions are "orange peel" coupling and "demag" fields.

"Orange peel" coupling originates with the roughness of the bottom FM layer. This process is shown schematically in Figure 3. A transmission electron micrograph (TEM) of a SDT junction is shown on the left. The alumina barrier shows as a lighter contrast. The bottom FM exhibits columner growth, causing the grains to bow upward at the surface of the bottom electrode. This bowing produces magnetic poles on the edges, as drawn schematically (in red) in the cartoon on the right side of Fig. 3. These poles produce a magnetic field in the top FM layer in the same direction as the magnetization of the pinned FM layer. This field is the cause of the ferromagnetic coupling between the layers. The net result of this coupling on the electrical response is that the curve in Fig. 2 is shifted to the left. There is an offset of the center of the loop toward negative fields, such that the resistance at zero field is a low resistance state.

On the other hand, "demag" fields are the magnetic fields emanating from the edges of the bottom FM electrode. Since the magnetic field wants to complete a circuit, fields emanating from the bottom FM layer terminate on the sense FM layer, producing a field in the opposite direction of the pinned film's magnetization. This induced field is largest at the edges of the sense layer. This process is shown schematically in Figure 4, where the thick arrow designates the magnetization of the bottom FM layer, and the thin arrows designate the emanating fields, and the induced field in the sense FM layer. This demagnetization field causes antiferromagnetic (AF) coupling, which tends to move the electrical response curve of Fig. 2 towards positive fields, such that the resistance of the device at zero field is a high resistance state. As indicated by Figure 4, as the device size gets smaller, the fraction of the sense layer affected by the induced field is greater, and thus the AF coupling increases as the device size decreases.



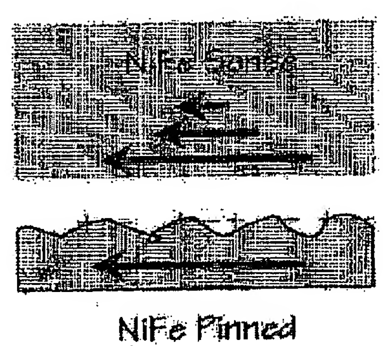


Figure 3: Origin of "orange peel" coupling. Bowing of the grains in the bottom, pinned NiFe electrode produces coupling fields in the sense NiFe layer.
TEM Photo courtesy of Xavier Portier, Oxford University.

Inventor: [signature] Date 6-3-95

Witness: [signature] Date 8/24/99

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In the absence of "orange peel" coupling, the SDT junction is expected to reside in the AF coupled state. However, in real devices, especially those fabricated with a pinning layer on the bottom, the FM coupling is great enough to mask the AF state, even at very small device sizes (0.25 µm).

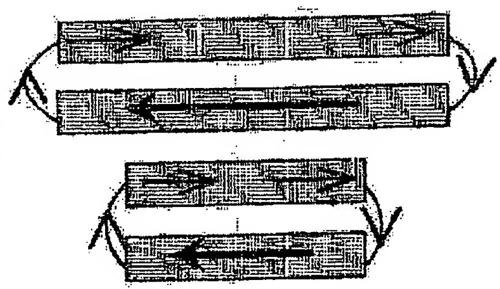

Figure 4: Schematic representation of demagnetization fields. A field caused by the magnetization of the bottom FM layer terminates on the sense FM layer, inducing a field in the opposite direction to the magnetization of the bottom FM. Decreasing the size of the SDT junction increases the volume of the sense layer affected by the fields.

Removal or reduction of the bowing in the bottom electrode has several benefits over the state of the art processing techniques. First, it reduces the strong FM coupling between the pinned and sense layer. Also, since the resistance is exponentially dependent on the barrier thickness, and since bowing causes variations in the barrier thickness, bowing also causes variations in resistance from device to device. When the Al is deposited it fills in-between the grains, then on top of the grains. So the thickness of the barrier in the valley areas is greater than at the peaks. Thus the bulk of the tunneling current comes from the peak areas and the resistance is greatly dependent on the local topography. Extreme variations in barrier thickness, or equivalently in grain peak height, can cause shorting of the device. So the second improvement obtained is uniform resistance, and the third is greater yield of working junctions in the MRAM arrays. Finally the forth benefit is the lowering the resistance of the devices. Since the barrier material is distributed more homogeneously, the nominal barrier thickness can be reduced, thereby reducing the device resistance.

These benefits are realized by removing the "orange peel" FM coupling from the device. The novel process reported here of ion etching the bottom FM layer before deposition of the barrier material accomplishes this objective. Devices processed in this manner exhibit the inherent AF coupling of the device, higher resistance for the same thickness of deposited Al for the barrier, lower variation of resistance from device to device, and a higher yield of working devices. These benefits are realized by smoothing the surface of the bottom electrode, and decreasing the angle on the edges of the grain, by the ion etch process.

The proposed process is implemented as follows. The ion etch rate of the material used for the pinned FM layer is determined. The thickness of the deposited pinned FM layer is then increased to compensate for the ion etch rate of the material, for the specific amount of time the ion etch will be performed. For example, the ion etch rate of our system on NiFe is ~0.8 nm/min. For a 5 minute ion etch, we deposit an extra (0.8 nm/min x 5 min =) 4 nm for the pinned FM layer. After deposition of this modified pinned FM layer, and before the deposition of the barrier material, an ion etch on the bottom electrode is done for the specified amount of time. The ion-etch process decreases the roughness of the bottom electrode, and therefore decreases the FM coupling between the layers. After a critical flatness of the electrode has been achieved, further ion etching then increases the roughness and FM coupling.

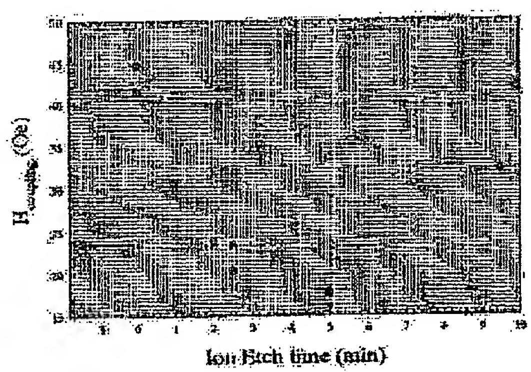

Figure 5: Coupling fields as a function of ion-etch time before deposition of barrier material. Two experiments were performed at zero and 2.5 minutes, confirming the decrease in coupling field with ion etch time.

This process has been performed on material stacks deposited on SiO_2 squares as well as for device junctions. As expected, the ion etch process is observed to decrease the FM coupling

Inventor: Lance Nickel Date 6-3-99

Witness: [signature] Date 6/4/99

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initially, then the coupling increases again at longer ion etch times. These results are summarized in Figure 5. The samples represented in Figure 5 are SDT materials stacks deposited as depicted in Figure 1 (with no interfacial layer) on SiO_2 squares, with the added steps of: 1) increasing the thickness of the pinned FM layer; and 2) an ion etch process step. The ion etch was performed in situ directly after the deposition of the pinned FM layer. The samples in Fig. 5 have r-f sputtered Al_2O_3 barriers (as opposed to deposition of Al followed by plasma oxidation). In this data the coupling field decreases monotonically for up to 5 minutes of ion etch time, after which the coupling field increases again. These data show a decrease from >40 Oe offset to ~18 Oe offset: a decrease of over a factor of 2.

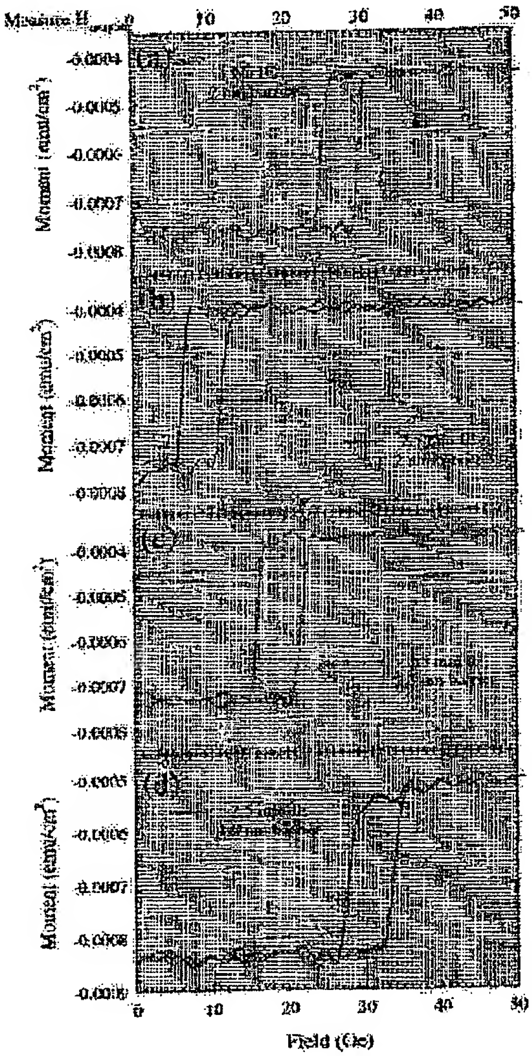

Figure 6: Magnetization curves of the sense layer of a series of samples with plasma oxidized barriers. (a), standard sample with 15 A Al deposited for barrier (20 A after oxidation); (b) same as (a) except for ion etch procedure performed before deposition of Al; (c) ion etch procedure, 10 A Al deposited; (d) ion etch procedure, 7.5 A Al deposited for barrier.

Similar results are obtained for samples with plasma oxidized barriers. The magnetization vs. magnetic field of a series of these samples is shown in Figure 6. Panels (a) and (b) are two samples with the same materials set and barrier thickness, with sample (b) undergoing the ion etch (IE) process prior to deposition of the barrier. This data shows that the FM coupling is reduced by a factor of three (from ~27 Oe down to ~9 Oe) for the sample with a 2.5 minute ion etch.

One of the added benefits discussed above is that by reducing the roughness of the bottom electrode it is possible to decrease the barrier thickness. Reduction of the roughness means that the Al is distributed more evenly over the bottom electrode, and there are less likely to be large protrusions that prevent homogeneous coverage, and cause shorting. This is demonstrated in Figure 6, where samples (c) and (d) have the barrier reduced to 1.3 and 1.0 nm of Al_2O_3 without pinholes (which would show up as very large coupling). As the barrier thickness decreases, the FM offset increases, since the sense FM layer is now closer to the coupling field source.

The morphology of the top of the pinned FM layer has been measured directly by Atomic Force Microscopy (AFM). The results for samples prepared with and without the ion etch procedure are presented in Figure 7. Here the depth is indicated by the shaded color: the lighter the color, the higher the topography. The difference between the two samples is readily apparent. The standard sample has deep valleys and high peaks in the columnar grain structure. Measurements of peak to valley height show it to be on the order of 15 A. The edges of the grains are also very sharp, which tends to form many magnetic poles.

The morphology of the sample with the ion etch procedure is markedly different. The peaks of the grains are much more rounded, with a larger radius of curvature. The areas between the

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Witness: [signature] Date: 6/4/99

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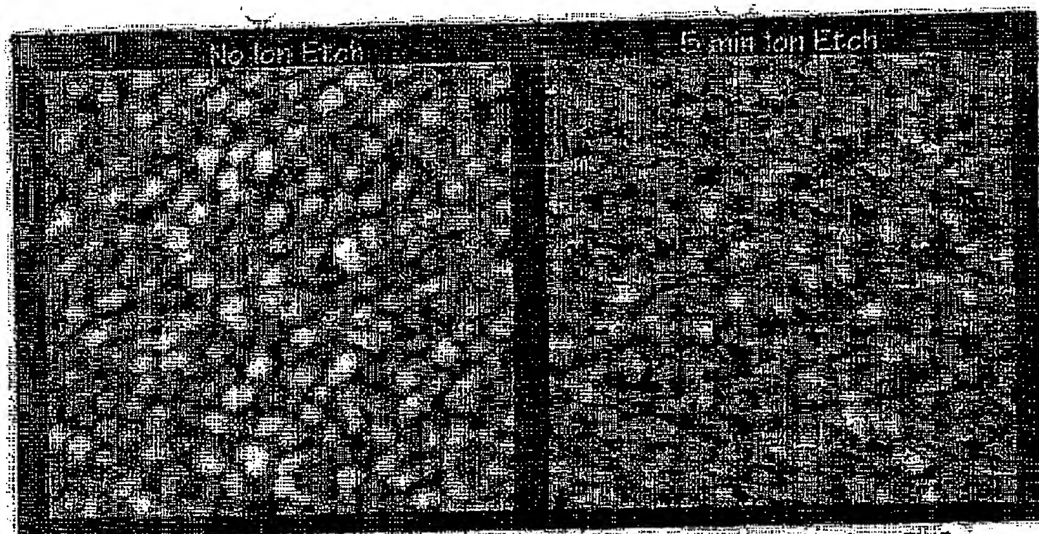

Figure 7: Atomic Force Microscope images of the topography of the pinned FM surface. Shading indicates height: dark is low, light is high. With no ion etch process, the variation in peak to valley is ~15 Angstroms. With the ion etch procedure the variation is ~9 Angstroms. The morphology of the sample with the ion etch procedure is much flatter, with a larger radius of curvature for the grains, which is expected to produce fewer magnetic poles. AFM micrographs courtesy of Doug Gilberg, Hewlett-Packard Laboratories.

grains are flat, as contrasted to the deep valleys in the standard sample. The measured peak to "valley" distance on this sample is 9 Angstroms, significantly smaller than that of the standard sample. The larger radius of curvature produces shallower angles for the grains, which is expected to produce fewer magnetic poles.

SDT junctions using this novel processing technique have been prepared, as well as arrays of SDT junctions. The sample preparation details are given in Table I. Sample A is the control sample that had no ion etch procedure during deposition. Sample B is identical to sample A, except it has an ion etch step. Sample C has an ion etch step, and the alumina tunnel barrier has been thinned.

Table I: Processing details for samples using ion etch (IE) procedure.

Sample	Structure: element deposited or process performed; thickness (nm) or time (min)									
A (control)	IE /	Ta /	NiFe /	MnFe /	NiFe /		Al /	plasma oxidation /	NiFe /	Ta
	10:00	5	6	10	4		1.25	2:30	4	5
B	IE /	Ta /	NiFe /	MnFe /	NiFe /	IE /	Al /	plasma oxidation /	NiFe /	Ta
	10:00	5	6	10	8	5:00	1.25	2:30	4	5
C	IE /	Ta /	NiFe /	MnFe /	NiFe /	IE /	Al /	plasma oxidation /	NiFe /	Ta
	10:00	5	6	10	8	5:00	1.0	1:30	4	5

Compare first samples A and B. The resistance of Sample A is 16 times smaller than the resistance of Sample B. Specifically, the resistance of Sample A is 46.6 kΩ-μm² and that of Sample B is 742 kΩ-μm². This result indicates that the barrier of Sample B, which underwent the ion etch process, is more uniform than that of Sample A.

Sample C has a thinned barrier relative to Samples A and B. It has a resistance of 9 kΩ-μm². The electrical response of Sample C is shown in Figure 8. The device size of the sample is 0.75 x 1.5 μm². The center of the hysteresis loop is shifted ~1.5 Oe towards the positive field direction, and is thus AF coupled, as expected by micromagnetic modeling for a device without FM coupling. It is noted that the device is AF coupled even with the decreased barrier thickness. This is the first instance that we have observed AF

Inventor: Manish Nickel Date: 6-3-99

Witness: [illegible] Date: 6/4/99

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coupling in SDT junction devices. Furthermore, the AF coupling increases with decreasing device size, as expected. A 0.6 μm x 0.6 μm device has an AF coupling field of +43 Oe.

These results show that the FM coupling in SDT devices is reduced by the ion etch procedure such that they are AF coupled at zero field. This result is expected since the ion etch process flattens the bottom electrode, causing less production of magnetic poles, and producing a more uniformly thick barrier.

Furthermore, the ion etch process does not significantly affect the TMR properties. The TMR ratio of this device is 26.5%, which is comparable to values obtained in samples with identical materials set, but without the ion etch process.

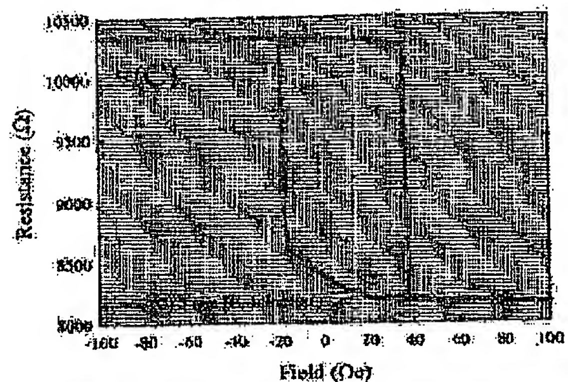

Figure 8: Electrical response of a device from Sample (C), which underwent ion-etch process and has a thinned barrier. The device is antiferromagnetically coupled, indicating the "orange peel" ferromagnetic coupling is essentially non-existent, even for the thin barrier device.

This process allows us to tune the magnetic properties of the device. As mentioned above, the AF coupling increases as the device size decreases. Figure 5 shows that the FM coupling is reduced monotonically with ion etch time. This means that the ion etch time can be adjusted to allow the FM coupling to exactly compensate for the AF coupling, no matter what device size is used at the design center of the application. This permits adjustment of the magnetic interactions such that the electrical response hysteresis curve is centered about zero field. This is a very important capability in order to produce magnetic memory, or other devices, and represents a significant improvement to prior art in the field.

MRAM arrays consisting of SDT devices have also been fabricated. The resistance of the devices in the MRAM array structure is very uniform. For arrays of 64 x 64 devices, we find the device resistance is within 8% Ω across the array. This is compared to arrays without the ion etch process which show resistance variations of 28% Ω. Furthermore, the number of shorts detected in the arrays is greatly reduced. This process allows us to improve the uniformity of the device resistance in the MRAM arrays, and improve the device yield. This is a significant improvement over the prior art in the field.

Inventor: [signature] Date 6-3-95

Witness: [signature] Date 6/2/95

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FORM PTO-1449 (Modified)	Docket No.: 10991744-4	Serial No.: 09/981,277
LIST OF PATENTS AND PUBLICATIONS FOR APPLICANT'S INFORMATION DISCLOSURE STATEMENT	Applicant: Janice Nickel Title: METHOD OF FABRICATING AN MRAM DEVICE INCLUDING SDT JUNCTION MEMORY CELLS	
	Filing Date: 10/17/2001	Art Unit: 2822

UNITED STATES PATENT DOCUMENTS

*Exr's. Inits.	Ref	Patent No.	Date	Name	Class	Sub Class	Filing Date (if applicable)
	AA	6,292,389	9/18/2001	Chen et al.			
	AB						
	AC						
	AD						
	AE						
	AF						
	AG						
	AH						
	AI						
	AJ						
	AK						

FOREIGN PATENT DOCUMENTS

Exr's. Init.	Ref	Document No.	Date	Country	Class	Sub	Translation? Yes	No
	AL							
	AM							
	AN							

OTHER REFERENCES (Including Author, Date, Title, Pertinent Pages, Etc.)

Exr's. Inits.	Ref	Bibliographic Data
	AO	U.S. Serial No. 08/974,925 filed 11/20/97 ("SOLID-STATE MEMORY WITH MAGNETIC STORAGE CELLS")
	AP	
	AQ	
	AR	

Examiner	Date Considered

* Examiner: Initial if citation considered, whether or not citation is in conformance with M.P.E.P. ¶ 609. Draw line through citation (i.e., ~~citation~~) if not in conformanc and not considered. Include copy of this form with next communication to applicant.

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US006292389B1

(12) **United States Patent**
Chen et al.

(10) **Patent No.:** **US 6,292,389 B1**
(45) **Date of Patent:** **Sep. 18, 2001**

(54) **MAGNETIC ELEMENT WITH IMPROVED FIELD RESPONSE AND FABRICATING METHOD THEREOF**

(75) Inventors: **Eugene Youjun Chen**, Gilbert; **Jon Michael Slaughter**, Tempe, both of AZ (US); **Jing Shi**, Salt Lake City, UT (US)

(73) Assignee: **Motorola, Inc.**, Schaumburg, IL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/356,864**

(22) Filed: **Jul. 19, 1999**

(51) **Int. Cl.**[7] **H01L 29/76**; G11C 11/14
(52) **U.S. Cl.** **365/158**; 365/171; 365/173; 257/295
(58) **Field of Search** 257/295; 365/171, 365/173, 158

(56) **References Cited**

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"Spin dependent tunnel/spin-valve devices with different pinning structures made by photolithography," Wang et al, Journal of Applied Physics, Bo. 85, No. 8, Apr. 1999, pp. 5255–5257.

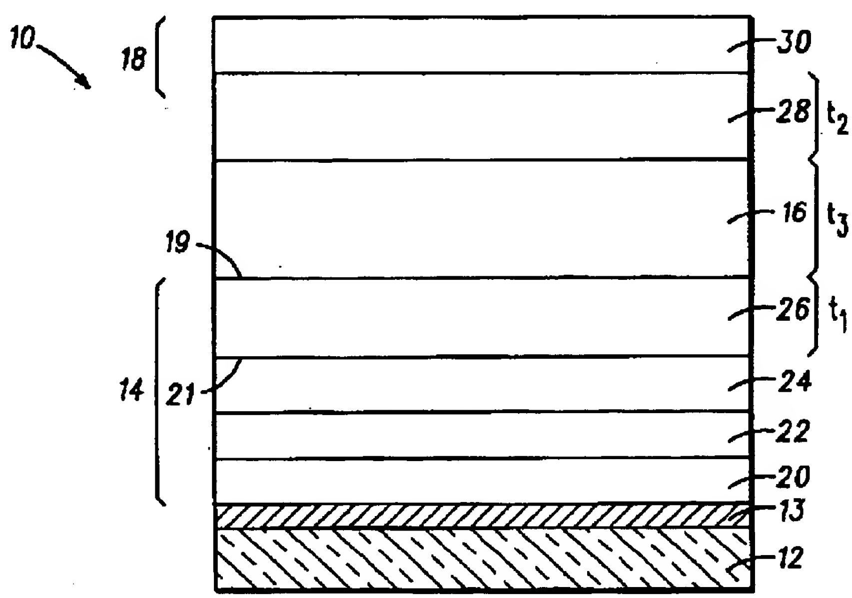
* cited by examiner

Primary Examiner—Minh Loan Tran
(74) *Attorney, Agent, or Firm*—William E. Koch

(57) **ABSTRACT**

An improved and novel fabrication method for a magnetic element, and more particularly a magnetic element (10) including a first electrode (14), a second electrode (18) and a spacer layer (16). The first electrode (14) includes a fixed ferromagnetic layer (26) having a thickness t_1. A second electrode (18) is included and comprises a free ferromagnetic layer (28) having a thickness t_2. A spacer layer (16) is located between the fixed ferromagnetic layer (26) and the free ferromagnetic (28) layer, the spacer layer (16) having a thickness t_3, where $0.25t_3<t_1<2t_3$, thereby producing near zero magnetic field at the free ferromagnetic layer (28).

18 Claims, 3 Drawing Sheets



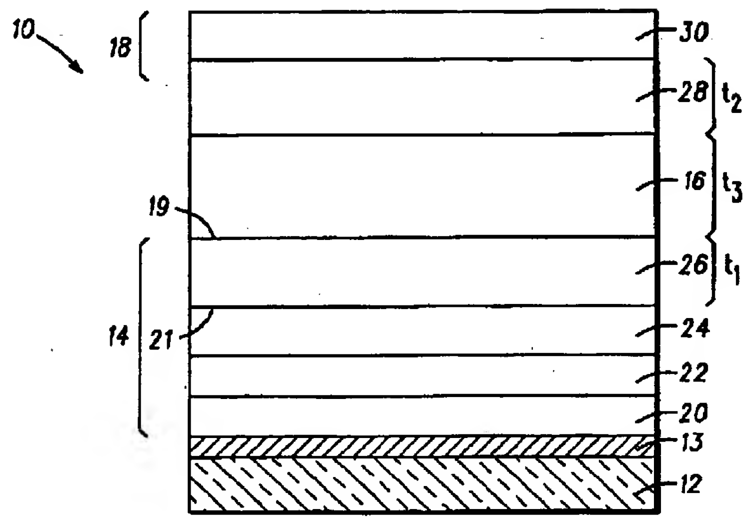


FIG. 1

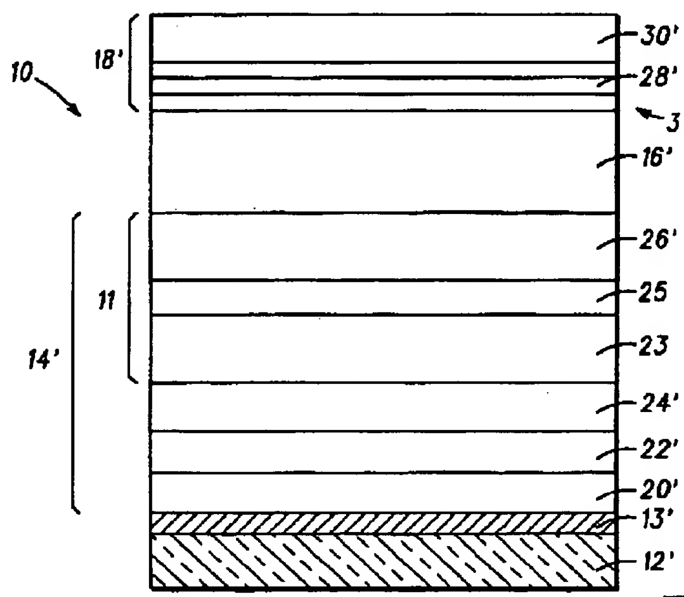


FIG. 2

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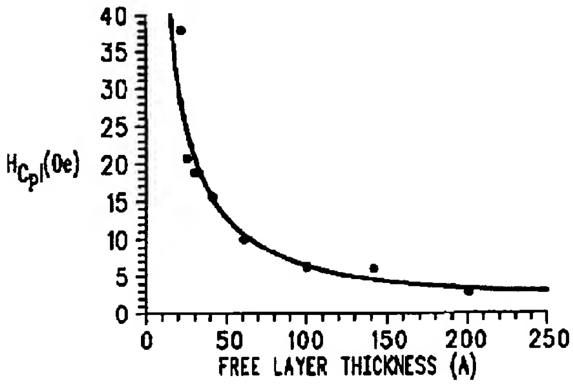

FIG. 3

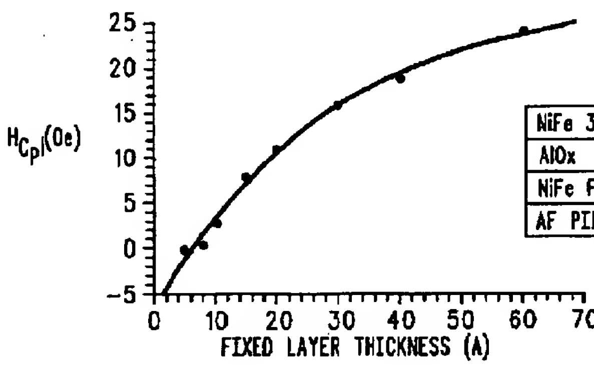

FIG. 4

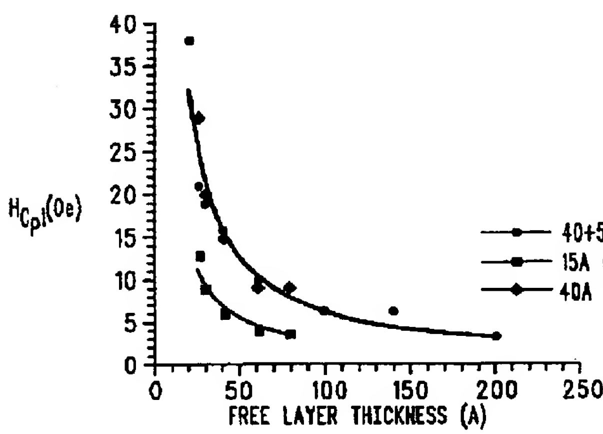

FIG. 5

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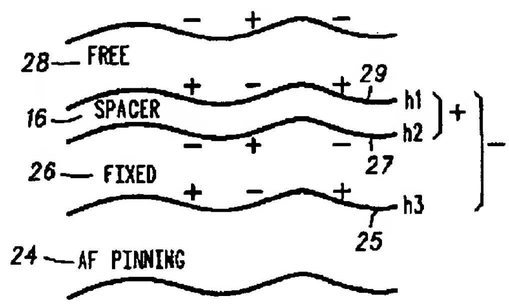

FIG. 6

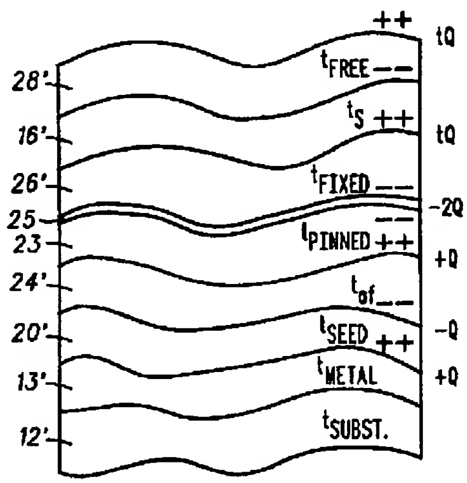

FIG. 7

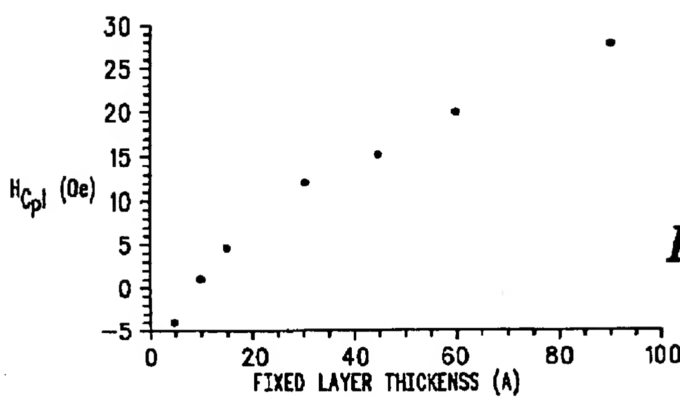

FIG. 8

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MAGNETIC ELEMENT WITH IMPROVED FIELD RESPONSE AND FABRICATING METHOD THEREOF

FIELD OF THE INVENTION

The present invention relates to magnetic elements for information storage and/or sensing and a fabricating method thereof, and more particularly, to a method of fabricating and thus defining the magnetic element to improve magnetic field response.

BACKGROUND OF THE INVENTION

This application is related to a co-pending application that bears U.S. Pat. No. 5,940,319, entitled "MAGNETIC RANDOM ACCESS MEMORY AND FABRICATING METHOD THEREOF," filed on Aug. 31, 1998, assigned to the same assignee and incorporated herein by this reference, co-pending application that bears U.S. Pat. No. 6,024,885, entitled "PROCESS OF PATTERNING MAGNETIC FILMS" filed on Dec. 8, 1997, assigned to the same assignee and incorporated herein by this reference and issued U.S. Pat. No. 5,768,181, entitled "MAGNETIC DEVICE HAVING MULTI-LAYER WITH INSULATING AND CONDUCTIVE LAYERS", issued Jun. 16, 1998, assigned to the same assignee and incorporated herein by this reference.

Typically, a magnetic element, such as a magnetic memory element, has a structure that includes ferromagnetic layers separated by a non-magnetic layer. Information is stored as directions of magnetization vectors in magnetic layers. Magnetic vectors in one magnetic layer, for instance, are magnetically fixed or pinned, while the magnetization direction of the other magnetic layer is free to switch between the same and opposite directions that are called "Parallel" and "Antiparallel" states, respectively. In response to Parallel and Antiparallel states, the magnetic memory element represents two different resistances. The resistance has minimum and maximum values when the magnetization vectors of the two magnetic layers point in substantially the same and opposite directions, respectively. Accordingly, a detection of changes in resistance allows a device, such as an MRAM device, to provide information stored in the magnetic memory element. The difference between the minimum and maximum resistance values, divided by the minimum resistance is known as the magnetoresistance ratio (MR).

An MRAM device integrates magnetic elements, more particularly magnetic memory elements, and other circuits, for example, a control circuit for magnetic memory elements, comparators for detecting states in a magnetic memory element, input/output circuits, etc. These circuits are fabricated in the process of CMOS (complementary metal-oxide semiconductor) technology in order to lower the power consumption of the device.

In addition, magnetic elements structurally include very thin layers, some of which are tens of angstroms thick. The performance of the magnetic element is sensitive to the surface conditions on which the magnetic layers are deposited. Accordingly, it is necessary to make a flat surface to prevent the characteristics of a magnetic element from degrading.

During typical magnetic element fabrication, such as MRAM element fabrication, which includes metal films grown by sputter deposition, evaporation, or epitaxy techniques, the film surfaces are not absolutely flat but instead exhibit surface or interface waviness. This waviness of the surfaces and/or interfaces of the ferromagnetic layers is the cause of magnetic coupling between the free ferromagnetic layer and the other ferromagnetic layers, such as the fixed layer or pinned layer, which is known as topological coupling or Néel's orange peel coupling. Such coupling is typically undesirable in magnetic elements because it creates an offset in the response of the free layer to an external magnetic field.

The ferromagnetic coupling strength is proportional to surface magnetic charge density and is defined as the inverse of an exponential of the interlayer thickness. As disclosed in U.S. Pat. No. 5,764,567, issued Jun. 9, 1998, and entitled "MAGNETIC TUNNEL JUNCTION DEVICE WITH NONFERROMAGNETIC INTERFACE LAYER FOR IMPROVED MAGNETIC FIELD RESPONSE", by adding a non-magnetic copper layer next to the aluminum oxide tunnel barrier in a magnetic tunnel junction structure, hence increasing the separation between the magnetic layers, reduced ferromagnetic orange peel coupling, or topological coupling, is achieved. However, the addition of the copper layer will lower the MR of the tunnel junction, and thus degrade device performance. In addition, the inclusion of the copper layer will increase the complexity for etching the material.

Accordingly, it is a purpose of the present invention to provide an improved magnetic element with improved field response.

It is another purpose of the present invention to provide an improved magnetic element that includes reduced ferromagnetic coupling, more particularly ferromagnetic coupling of topological origin.

It is a still further purpose of the present invention to provide a method of forming a magnetic element with improved field response.

It is still a further purpose of the present invention to provide a method of forming a magnetic element with improved field response which is amenable to high throughput manufacturing.

SUMMARY OF THE INVENTION

These needs and others are substantially met through provision of a magnetic element including a first electrode, a second electrode and a spacer layer. The first electrode includes a fixed ferromagnetic layer whose magnetization is fixed in a preferred direction in the presence of an applied magnetic field, the fixed ferromagnetic layer having a thickness t_1. A second electrode is included and comprises a free ferromagnetic layer whose magnetization is free to rotate in the presence of an applied magnetic field, the free ferromagnetic layer having a thickness t_2. A spacer layer is located between the fixed ferromagnetic layer of the first electrode and the free ferromagnetic layer of the second electrode for permitting tunneling current in a direction generally perpendicular to the fixed and free ferromagnetic layers, the spacer layer having a thickness t_3, where $0.25t_3<t_1<2t_3$, such that the net magnetic field at the interface between the free layer and the spacer layer, due to the topology of the other ferromagnetic surfaces, is near zero. The magnetic element further includes a metal lead and a substrate, the metal lead, the first and second electrodes and the spacer layer being formed on the substrate. Additionally disclosed is a method of fabricating the magnetic element with improved field response.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1 and 2 show cross-sectional views of a magnetic element with improved field response according to the present invention;

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FIGS. 3–5 illustrate the coupling field with respect to thickness of the metal film layers;

FIG. 6 illustrates the creation of magnetic poles by forming interface roughness;

FIG. 7 illustrates the magnetic poles created by adjusting the interface roughness of the metal film layers of the magnetic element according to the present invention; and

FIG. 8 illustrates the experimental results of the topological coupling field versus the fixed magnetic layer thickness according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

During the course of this description, like numbers are used to identify like elements according to the different figures that illustrate the invention. FIGS. 1 and 2 illustrate in cross-sectional views a magnetic element according to the present invention. More particularly, illustrated in FIG.1, is a fully patterned magnetic element structure 10. The structure includes a substrate 12, a base electrode multilayer stack 14, a spacer layer 16 including oxidized aluminum, and a top electrode multilayer stack 18. It is additionally disclosed that spacer layer 16 includes either a dielectric material defining a MTJ structure or a conductive material defining a spin valve structure. Base electrode multilayer stack 14 and top electrode multilayer stack 18 include ferromagnetic layers. Base electrode layers 14 are formed on a metal lead 13, which is formed on a substrate 12. Base electrode layers 14 include a first seed layer 20, deposited on metal lead 13, a template layer 22, a layer of antiferromagnetic pinning material 24, and a fixed ferromagnetic layer 26 formed on and exchange coupled with the underlying antiferromagnetic pinning layer 24.

Ferromagnetic layer 26 is described as fixed, or pinned, in that its magnetic moment is prevented from rotation in the presence of an applied magnetic field. Ferromagnetic layer 26 is typically formed of alloys of one or more of the following: nickel (Ni), iron (Fe), and cobalt (Co) and includes a top surface 19 and a bottom surface 21. Top electrode stack 18 includes a free ferromagnetic layer 28 and a protective layer 30. The magnetic moment of the free ferromagnetic layer 24 is not fixed, or pinned, by exchange coupling, and is free to rotate in the presence of an applied magnetic field. Free ferromagnetic layer 28 is typically formed of alloys of one or more of the following: nickel (Ni), iron (Fe) and cobalt (Co). Fixed ferromagnetic layer 26 is described as having a thickness of t_1, wherein t_1 is typically within a range of 5–40 Å. Free ferromagnetic layer 28 is described as having a thickness of t_2, wherein t2 is generally less than 50 Å. Spacer layer 16 is described as having a thickness of t_3, wherein t3 is generally less than 20 Å for magnetic tunnel junction structures or less than 40 Å for spin valve structures or the like. During fabrication, t_1 is chosen such that the magnetic fields produced by the topology of top surface 19 and bottom surface 21 of fixed ferromagnetic layer 26 cancel to produce near zero coupling energy between free ferromagnetic layer 28 and fixed ferromagnetic layer 26. It should be understood that a reversed, or flipped, structure is anticipated by this disclosure. More particularly, it is anticipated that the disclosed magnetic element can be formed to include a top fixed, or pinned layer, and thus described as a top pinned structure.

Illustrated in FIG.2, is an alternative embodiment of a fully patterned magnetic element structure, referenced 10', including a synthetic antiferromagnetic structure 11. Again, it should be noted that all components of the first embodiment that are similar to components of the second embodiment, are designated with similar numbers, having a prime added to indicate the different embodiment. Similar to the structure described with regard to FIG. 1, this structure includes a substrate 12', a base electrode multilayer stack 14', a spacer layer 16', and a top electrode multilayer stack 18'. Base electrode multilayer stack 14' and top electrode multilayer stack 18' include ferromagnetic layers, generally similar to stack 14 and 18 of FIG. 1. Base electrode layers 14' are formed on a metal lead 13', which is formed on a substrate 12' and includes a first seed layer 20', deposited on metal lead 13', a template layer 22', a layer of antiferromagnetic material 24', a pinned ferromagnetic layer 23 formed on and exchange coupled with the underlying antiferromagnetic layer 24', a coupling layer 25, and a fixed ferromagnetic layer 26' which is antiferromagnetically coupled to the pinned layer. Ferromagnetic layer 23 and 26' are described as fixed, or pinned, in that their magnetic moment is prevented from rotation in the presence of an applied magnetic field. Top electrode stack 18 includes a free ferromagnetic layer 28' and a protective layer 30'. The magnetic moment of the free ferromagnetic layer 28' is not fixed, or pinned, by exchange coupling, and is free to rotate in the presence of an applied magnetic field. It is disclosed that free ferromagnetic layer 28', includes a Ru antiferromagnetically coupled trilayer 31 as illustrated in FIG. 2.

Fixed ferromagnetic layer 26' is described as having a thickness of t_1. Free ferromagnetic layer 28' is described as having a thickness of t_2. Spacer layer 16' is described as having a thickness of t_3. It should be understood that a reversed, or flipped, structure is anticipated by this disclosure. More particularly, it is anticipated that the disclosed magnetic element with SAF structure can be formed to include a top fixed, or pinned layer, and thus described as a top pinned structure.

Referring now to FIG. 3, a diagrammatic illustration is provided showing the effect of the thickness of the free ferromagnetic layer, such as layer 28 of FIG. 1, and the relative coupling field of the magnetic element. Magnetic elements typically utilized in information storage and/or sensing devices necessitate the use of thin free layers to maintain low switching fields. Yet, as illustrated in FIG. 3, when designing devices with these thin free layers, the coupling field H_{cpl} is increased. The coupling field as illustrated increases as $1/d_{free}$, where d is the thickness of the free layer such as 28 or 28'. Accordingly, to lower the coupling field H_{cpl}, adjustments can be made in the remaining structure of the magnetic element as disclosed herein.

Referring to FIG. 4, illustrated is the reduction in the coupling field H_{cpl} by adjusting the thickness of the fixed layer, such as layer 26 of FIG. 1. As illustrated, by decreasing the thickness of the fixed layer, the coupling field H_{cpl} is decreased, approaching near zero. Accordingly, and as illustrated in FIG. 5, a magnetic element, generally similar to magnetic element 10 of FIG. 1, having included in addition to free layer 18, a fixed layer having a thickness of 15 Å will provide for a dramatic lowering shift in the Hcpl curve, hence the ability to achieve near zero coupling.

In addition, as illustrated in FIG. 6, by adjusting the roughness of the interface of the pinning layer in a structure such as that disclosed as magnetic element 10 of FIG. 1, a decrease in the magnetic field response coupling can be achieved. Referring more specifically to FIG. 6, h3 is the waviness amplitude of an interface surface 25 of AF pinning layer 24 most remote from free layer 28, h2 is the waviness amplitude of an interface surface 27 of fixed ferromagnetic layer 26, closest to free ferromagnetic layer 28, and h1 is the

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waviness amplitude of an interface surface 29 of spacer layer 16, closest to free ferromagnetic layer 28. Magnetic poles are created by the interface roughness, hn, with period λ. Interface surface 27 of fixed layer 26 couples positively to interface surface 29 of free layer 28. Interface surface 25 of AF pinning layer 24 couples negatively to interface surface 29 of free layer 28. The Hcpl depends on h3/h2, the thickness of fixed layer 26 and the λ. By increasing the roughness of h3 so that h3>h2, near zero coupling can be further achieved in magnetic element 10. More specifically, when h3>h2, there will be one point with respect to the thickness of fixed layer 26, where the field response coupling will exactly cancel the magneto-static coupling which is zero at $d_{fixed}=0$.

The roughness of interface 25, or h3, can be adjusted by increasing or decreasing the thickness of pinning material 24, ion bombardment, or deposition of a third material. More specifically, the roughness of pinning material 24 can be increased or decreased by making pinning material 24 thinner or thicker, wherein, fixed layer 26 must "heal" the roughness to result in h3>h2. Typically nickel iron (NiFe) will result in proper "healing" to result in h3>h2. Utilizing an alternative method to adjust the roughness of interface surface 25, ion bombardment is utilized to either roughen pinning material 24 or smooth surface 27 of pinned material 26. Finally, the adjustment of roughness can be achieved by depositing a small amount of a third material between pinning layer 24 and fixed layer 26 to increase h3, particularly if the material grows with an island-like structure.

Next, it is disclosed that the use of non-magnetic seed and template layers (20 and 22) will result in a decrease in the magnetic field response coupling without the need for the inclusion of a SAF structure. The template layer will add no moment to the structure, thus the only magneto-static coupling is a result of the thin pinned layer included within the structure. Accordingly, adjustments can be made for the canceling of the level of coupling to achieve near zero coupling. When template layer 22 is nonmagnetic, and there is no SAF, negative magnetostatic coupling due to poles at the ends of the patterned shape and positive Neel coupling controlled by the thickness of pinned layer 24. The thickness of pinned layer 24 could be chosen to offset the magnetostatic coupling giving a centered loop.

Finally, it is disclosed to include a high moment alloy, such as Ni(50%)Fe(50%) on at least one side of fixed ferromagnetic layer 26 to increase the negative coupling contribution to the total coupling effect.

Referring now to FIG. 7, illustrated is the structure of magnetic element 10' of FIG. 2 showing the magnetic poles created. During operation of magnetic element 10' as disclosed herein, when the total magnetic field from the poles at the interfaces other than the one at the origin of the y axis is near zero, then the topological coupling will be near zero. When the total field at the y axis origin is negative, then the topological coupling will be negative or antiferromagnetic in nature. Usually the total field at the y axis origin where the free magnetic layer lies is positive, thus causing ferromagnetic topological coupling. However, for the structure shown in FIG. 7, for certain conditions, particularly when the fixed layer thickness is thin, topological coupling can be zero or even negative.

The additional interface will produce an even stronger cancellation of the coupling from interface 27 than could be accomplished by interface 25 alone. Experimental results of the topological coupling field versus the fixed magnetic layer thickness are shown in FIG. 8. As the fixed magnetic

layer thickness decreases in the magnetic tunnel junction structure, the coupling field decreases, crosses zero, and finally becomes negative. Overall the layers in magnetic memory element 10 are very thin with magnetic layers varying from 3 to 200 Å.

Thus, a magnetic element with an improved field response and its fabrication method are disclosed in which the magnetic coupling is adjusted based on the thickness of the fixed ferromagnetic layer, and/or roughness of the interface surface of the fixed ferromagnetic layer relative to the remaining metal thin film structure. As disclosed, this technique can be applied to devices using patterned magnetic elements, such as magnetic sensors, magnetic recording heads, magnetic recording media, or the like. Accordingly, such instances are intended to be covered by this disclosure

What is claimed is:

1. A magnetic element comprising:

a first electrode comprising a fixed ferromagnetic layer having a top surface and a bottom surface whose magnetization is fixed in a preferred direction in the presence of an applied magnetic field, the fixed ferromagnetic layer having a thickness t_1;

a second electrode comprising a free ferromagnetic layer having a surface whose magnetization is free to rotate in the presence of an applied magnetic field, the free ferromagnetic layer having a thickness t_2;

a spacer layer located between the fixed ferromagnetic layer of the first electrode and the free ferromagnetic layer of the second electrode, the spacer layer having a thickness t_3;

wherein t_1 is chosen such that the magnetic fields produced by the topology of the top surface and the bottom surface of the fixed ferromagnetic layer cancel to produce near zero coupling energy between the free ferromagnetic layer and the fixed magnetic layer; and

a substrate, the first and second electrodes, and the spacer layer, being formed on the substrate.

2. A magnetic element as claimed in claim 1 wherein t_1 is chosen in the range, $0.25t_3<t_1<2t_3$, such that the magnetic fields produced by the topology of the surfaces of the fixed ferromagnetic layer cancel to produce the lowest coupling energy possible between the free ferromagnetic layer and the fixed ferromagnetic layers without degradation of the electrical properties of the device.

3. A magnetic element as claimed in claim 1 wherein the first electrode further comprises a pinned ferromagnetic layer and an antiferromagnetic pinning layer exchange coupled thereto, the pinned ferromagnetic layer and the antiferromagnetic pinning layer formed between the substrate and the fixed ferromagnetic layer, the pinned ferromagnetic layer having its magnetization fixed by antiferromagnetic exchange though a spacer layer, in a direction opposite the fixed ferromagnetic layer and thereby defining a SAF structure.

4. A magnetic element as claimed in claim 1 wherein the magnetization directions of the fixed and the free ferromagnetic layers are one of parallel or antiparallel to one another in the absence of an applied magnetic field.

5. A magnetic element as claimed in claim 1 wherein the free ferromagnetic layer and the fixed ferromagnetic layer include at least one of NiFe, NiFeCo, CoFe, or Co.

6. A magnetic element as claimed in claim 1 wherein the spacer layer includes one of a dielectric material defining a MTJ structure or a conductive material defining a spin valve structure.

7. A magnetic element as claimed in claim 1 further including a high moment material located at an interface of the fixed ferromagnetic layer and the spacer layer.

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8. A magnetic element as claimed in claim 1 wherein the fixed ferromagnetic layer is a high moment material.

9. A magnetic element as claimed in claim 1 wherein the free ferromagnetic layer includes an Ru antiferromagnetically coupled tri-layer.

10. A magnetic element as claimed in claim 1 wherein the spacer layer has a thickness of less than 20 Å.

11. A magnetic element comprising:

a fixed ferromagnetic layer including a top surface and a bottom surface whose magnetic moment is fixed in a preferred direction in the presence of an applied magnetic field, the fixed ferromagnetic layer having a thickness of t_1;

a free ferromagnetic layer whose magnetic moment is oriented generally perpendicular to the moment of the magnetic field and is free to rotate away from said perpendicular orientation in the presence of an applied magnetic field, the free ferromagnetic layer having a thickness of t_2; and

a spacer layer located between the fixed ferromagnetic layer and the free ferromagnetic, the spacer layer having a thickness of t_3;

wherein t_1 is chosen such that the magnetic fields produced by the topology of the top surface and the bottom surface of the fixed ferromagnetic layer cancel to produce near zero coupling energy between the free ferromagnetic layer and the fixed ferromagnetic layer.

12. A magnetic element as claimed in claim 11 wherein $0.25t_3<t_1<2t_3$.

13. A magnetic element as claimed in claim 11 further including a high moment material located at an interface of the fixed ferromagnetic layer.

14. A magnetic element as claimed in claim 11 wherein the fixed ferromagnetic layer is a high moment material.

15. A magnetic element as claimed in claim 11 wherein the free ferromagnetic layer includes an Ru antiferromagnetically coupled tri-layer.

16. A magnetic element as claimed in claim 11 wherein t3 has a thickness of less than 20 Å.

17. A magnetic element as claimed in claim 11 wherein the spacer layer includes one of a dielectric material defining a MTJ structure or a conductive material defining a spin valve structure.

18. A magnetic element as claimed in claim 11 including an AF pinning layer formed adjacent the fixed ferromagnetic layer, wherein the roughness of an interface h3 of the AF pinning layer, is greater than the roughness of an interface h2 of the fixed ferromagnetic layer, thereby decreasing the coupling field of the magnetic element.

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